Ultraviolet and Visible Detectors for Future Space Astrophysics Missions

A Report from the Ad-hoc, UV-Visible Detectors Working Group of NASA's Office of Space Science

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Prepared and edited by J. Chris Blades
Space Telescope Science Institute

MEMBERS OF THE AD-HOC WORKING GROUP
J. Chris Blades, Space Telescope Science Institute; Blas Cabrera, Stanford University; Phil Crane, NASA Headquarters; Chuck Joseph, Rutgers, The State University of New Jersey; Kathy Flanagan, Massachusetts Institute of Technology; Hashima Hasan, NASA Headquarters; Bob O'Connell, University of Virginia; Bedabrata Pain, Jet Propulsion Laboratory; Brad Peterson, Ohio State University and Bruce Woodgate, Goddard Space Flight Center

needs cooling

not rad hard, not solar

needs cooling, CTE los

— " —

Front-side illuminated?

cosmic ray hits higher than? co

10^3 high volts, only windowless

technology very immature

(high dark current)

gain depletion from glass plate

non-linearity at high counts

dynamic range, high voltage

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Preface: Working Group Charter

This report and the materials presented to the Group can be viewed and downloaded via the web at: www.stsci.edu/detectors

IN THE FALL OF 2000, NASA's Office of Space Science established an ad-hoc Working Group to seek advice about detectors for future ultraviolet and visible space astrophysics missions. The Working Group was asked to assess the research and technology developments needed to insure that detectors for the ultraviolet and visible (UV-Vis) spectral regions are available to achieve the mission goals in the NASA Theme Roadmaps and the National Research Council's Decadal Survey for 2000-2010, Astronomy and Astrophysics in the New Millennium.

The Working Group made an assessment of the current state of detector design and fabrication in the United States and overseas and looked at the technology research and development capability to address future requirements. In carrying out this assessment, the Working Group sampled various detector technologies and made a number of site visits, hearing from a selection of detector groups. The organizations that the Working Group visited, along with presentations received, can be found at: www.stsci.edu/detectors. The material that follows is the final report of the Group.

Supporting material comes from a conference entitled Space Astrophysics Detectors and Detector Technologies, held at the Space Telescope Science Institute, Baltimore in June 2000. At this conference a variety of current and emerging detector technologies were presented for the UV–Vis spectral range as well as other wavelength domains. Information about the conference can be found at the same website.

The Working Group was asked to provide a set of Findings to help prioritize future detector development programs; these Findings are presented in the next section. In addition, the Working Group identified a number of priorities and milestones for the coming decade to serve as a guide for UV-visible detector programs. The report is organized in sections according to the type of detector, and the corresponding development priorities and milestones are given in each applicable section. They are summarized in Section 7.

Summary: Findings of the Working Group

A. NO SINGLE CURRENT OR EMERGING detector technology covers, in any optimal way, the UV-Vis spectral region. A multifaceted approach is required for optimization of the desired spectral region. At the present time, CCDs (charge-coupled devices) are pre-eminent in the visible, while MCP (microchannel plate) devices and electron bombarded CCDs are the best choices for the solar-blind ultraviolet.

B. THE CCD MANUFACTURING BASE is declining in the United States. By contrast, there is substantial industrial interest in CMOS (Complementary Metal Oxide Semiconductor) Active Pixel Sensors (APS) as visible light detectors. For space astrophysics missions in the future, APS technology will offer many advantages over CCDs and we encourage development of science quality APS devices. CCDs should still be improved until CMOS APS technology is ready.

C. THE SENSITIVITY OF ULTRAVIOLET solar-blind detectors needs improvement. We find opportunities through development of a silicon-based MCP technology, new photocathode materials and use of AlGaN based detectors.

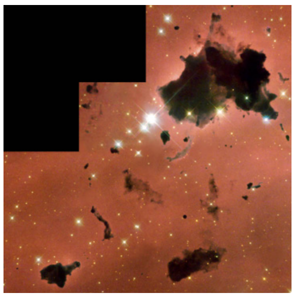
D. SUPERCONDUCTING DEVICES ARE UNIQUE astronomical detectors. They have good sensitivity over the entire UV-Vis wavelength range, provide simultaneous broad-band imaging, time tagging, and low resolution, high-efficiency spectroscopy. We find these superconducting devices likely to be an important class of detectors for space astrophysics in the long term.

E. INNOVATIVE IDEAS SHOULD BE SOUGHT for long wavelength blocking filters for efficient use in the ultraviolet with high-sensitivity panchromatic detectors such as CCDs, CMOS-APS and superconducting devices.

F. DETECTOR DEVELOPMENT IS BY FAR the most cost-effective way of improving the performance and efficiency of space missions. Promising new designs should be developed to flight readiness. By bridging the gap between laboratory proof of concept and flight readiness, and setting intermediate goals such as rocket and balloon flights, the risk of using new detectors is reduced and the costs of satellite missions are contained.

G. DETECTOR TECHNOLOGY REQUIRES maintaining a stable funding profile to protect the knowledge base and to keep expertise together. The long term nature of the work required to build astronomical detectors needs to be recognized and sustained.

1 Introduction

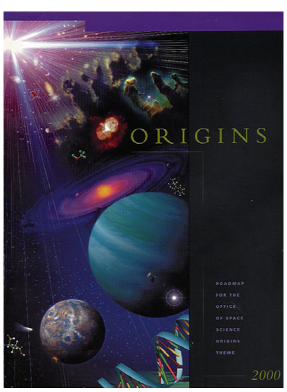


A composite filter image of Thackeray's Globules in IC 2944 obtained using CCDs on-board the Hubble Space Telescope. Acknowledgement: Hubble Heritage team. Details at: http://heritage.stsci.edu

THE HISTORY OF OBSERVATIONAL ASTRONOMY in the last fifty years is mainly one of expansion into new wavebands in the electromagnetic spectrum. From gamma rays to long wavelength radio, the full spectrum is now open to study by astronomers, allowing astonishing discoveries to be made. To capitalize on these breakthroughs and to understand the astrophysical ramifications, it has almost always been necessary to obtain corresponding observations in the UV-Vis spectral region.

The UV-Vis region covers wavelengths between 90 and 1000 nm. It contains the highest density of information on planets, stars, interstellar and intergalactic gas, and galaxies of any electromagnetic band. Consequently, the UV-Vis region has proven to be an essential adjunct to studies of the universe in other wavebands. The recent spectacular progress in understanding gamma ray bursts based on optical identifications is only one example. Access to the UV-Vis spectral region has enabled the Hubble Space Telescope (HST) to produce the unprecedented variety of images that have had such an impact on the public imagination. UV-Vis facilities in space will always be critical resources for the progress of astronomy.

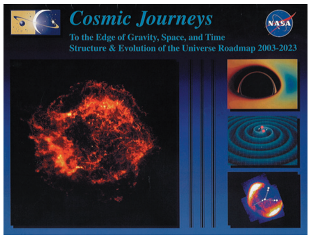
1.1 Current and Future UV-Vis Space Missions



The website http://space-science.nasa.gov gives access to the numerous science and technological programs managed by NASA, while details about NASA's Origins program are given at: http://origins.jpl.nasa.gov

TODAY, THE FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER (FUSE, operating from 90 – 119 nm) and HST (121 nm – 1.7 microns) cover the UV-visible and near-IR spectral regions. They will be joined soon by missions in development: the Galaxy Evolution Explorer (GALEX), an imaging and spectroscopic survey telescope designed for the 135-300 nm spectral region to study star formation, SPEAR, a nebular imaging spectrograph, covering the 90 – 180 nm wavelength region, designed for studying evolution of the Galactic plasma, and CHIPS, an EUV spectrograph also for studying the hot interstellar plasma. Changes to Hubble's instrument complement will occur in 2002 with the installation of the Advanced Camera for Surveys and in 2004 when the Cosmic Origins Spectrograph and Wide Field Camera 3 are scheduled for installation.

Future directions of space science in the United States will continue to be influenced by NASA's Origins Theme and Structure & Evolution of the Universe (SEU) Theme. The Origins objectives are to observe the birth of the earliest galaxies in the universe, to detect all planetary systems in our solar neighborhood, to find those planets that are capable of supporting life, and to learn whether life exists beyond our solar system. SEU science objectives include identifying the nature and origin of dark matter and dark energy; determining where and when the chemical elements were created; tracing the exchange of matter, energy, and magnetic fields between stars and the interstellar medium; understanding accretion jets and disks; and examining the limits of gravity and energy in the universe.



NASA's Roadmap for the Structure and Evolution of the Universe (SEU) Theme.

UV-Vis space missions in development include KEPLER, a wide field visible photometry mission using a large format CCD mosaic to search for planets around near-by stars; and SIM, which is designed to detect extra-solar planets using optical interferometry. The KEPLER focal plane array will consist of 21 CCD modules, and launch is baselined for 2006.

There are design concepts for very large UV-Vis missions beyond 2005. The concepts include SNAP (Supernova Acceleration Probe), designed around a wide-field telescope and employing a very large format optical CCD mosaic. SNAP will identify large numbers of distant supernovae from which the amount of cosmic dark energy can be determined. The visible camera of SNAP is designed to have more than 100 CCD modules located in an annulus nearly one-half metre wide, giving a 1 square degree field of view. The visible camera of SNAP is designed to have more than 100 CCD devices located in an annulus nearly one-half metre wide, giving a 1 square degree field to view. The Space Ultraviolet Visible Observatory, SUVO, is a proposed large aperture UV-Vis telescope intended for both imaging and spectroscopy. Major goals include study of the intergalactic medium from high redshift to the present epoch, with the potential of identifying the bulk of the baryons in the universe, which may reside in undetected form as hot gas. The Terrestrial Planet Finder, TPF, was originally conceived as an infrared interferometry mission, but recent studies suggest that operations in the UV-Vis band have good potential.

The success of these and future UV-Vis missions depend critically on the development of improved detector technology. New detector concepts must be shown to be feasible in a laboratory setting, and feasible designs must be translated into systems that are fully qualified for flight. Detector development is by far the most cost-effective way of improving the performance and efficiency of space missions.

Numerous books and articles describe the working details of astronomical detectors. The interested reader is referred to the following examples:

Carruthers, George R. 2000. "*Ultraviolet and X-ray detectors*." In *Electro-optics handbook*, edited by Ronald W. Waynant & Marwood N. Ediger. New York: McGraw-Hill, Inc.

Kitchin, Chris. R. 1998. *Astronomical Techniques*. Bristol: IOP Publishing Ltd.

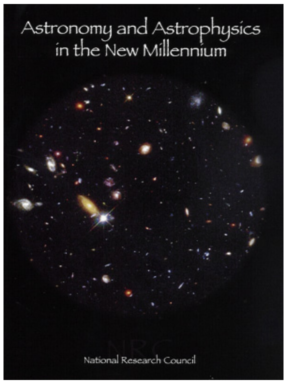
Joseph, Charles, L. 1999. *UV technology overview*. In *From X-rays to X-band: Space astrophysics detectors and detector technologies*, edited by J. Chris Blades. Available online at: http://www.stsci.edu/stsci/meetings/space_detectors/joseph.htm

1.2 Detector Classes

At the present time, no single detector technology is appropriate for all UV-Vis applications, and each technology has specific strengths and weaknesses. There are many different types of detectors in use, although they all belong to two basic classes: solid-state detectors and photo-emissive detectors.

In solid-state devices, the incident photon is absorbed into the bulk material, often causing an electron to transition into the conduction band where it can be manipulated and sensed. The most common solid-state devices are Silicon (Si) based CCDs. Their detection process requires energies of approximately an electron volt, giving these devices an excellent natural sensitivity in the visible. These detectors have read noise, and because they are sensitive to thermally induced backgrounds they must be cooled to well below room temperature.

Si CCDs are ubiquitous as visible light detectors; however, other solid-state materials and devices may emerge in the future as excellent choices for detectors in the ultraviolet. In particular, solid-state detectors made of Gallium Nitride (GaN) or other high-band-gap materials have the same properties as Si, but their activation energies are 3.4 eV or higher, thereby making these potential devices inherently solar blind and UV sensitive without thermal induced backgrounds.



The NRC Decadal Survey Committee, in addressing the need for an ultraviolet-optical space telescope after HST, specifically recommended: "an aggressive technology development program to develop UV detectors that are more sensitive, [and to develop] energy resolving detectors such as superconducting tunnel junctions or transition edge sensors."

Recently, superconduction sensors, a new subclass of solid-state detectors, have emerged. These ultracold (T<1K) devices include Superconducting Tunneling Junctions (STJ) and Transition Edge Sensors (TES). In STJs, an incident photon breaks a number of Cooper pairs proportional to its energy. These sensors provide for 3-dimensional imaging, two spatial as well as energy resolution, and in photon counting mode they also provide time resolution. The devices have good sensitivity over the entire UV-Vis and infrared regions.

In photo-emissive devices, the incident photon must have sufficient energy to eject an electron from the photocathode material, and this typically requires energies of a few electron volts. Such image sensors are therefore natural UV detectors and can be constructed to be inherently solar blind. The ejected photoelectron requires intensification for detection and this implies high voltages. Where the intensification process is saturated and has sufficient gain, detectors that are photon counting with zero read noise can be constructed. Microchannel plate (MCP) detectors are the most common of these devices in use at the present time.

There are also hybrid detector designs that combine features of both a photo-emissive front end and a solid-state back end in a single design. Examples of such devices include the photon counting intensified CCD, the Intensified Charge Injection Device (ICID), the intensified CMOS active pixel sensors and the Electron Bombarded CCD (EBCCD). Such devices seek the best of both worlds, but can increase design and fabrication complexity.

1.3 Current State-of-the-Art and Future Improvements

Astronomical detectors are required to have high sensitivity and low noise over the wavelengths of interest, good dynamic range, a large field of view and pixel sizes matched to the resolution. Operations in a space environment require excellent reliability, good engineering heritage, low power and low weight. The detector should be unaffected by the radiation environment. Performance characteristics of current flight detectors and potential future devices are compared in Table 1. Where possible, data from flight devices are used, and so these define the current state-of-the-art for space-qualified systems.

At optical wavelengths, CCDs have seen substantial improvements in sensitivity and format over the last decade. However, improvements to the read noise and dark count have been incremental at best, see Table 1. Generally, CCDs exhibit good dynamic range and have excellent reliability and flight heritage. However, they degrade in radiation environments, require cooling, are power hungry, and U.S. based foundries are in decline. As described later, CMOS Active Pixel Sensor devices offer solutions to many of the on-orbit disadvantages of CCDs. Although this new technology does not yet match current CCD performance, there is strong industrial interest in CMOS APS that indicates APS devices will eventually replace CCDs.

At ultraviolet wavelengths, detector sensitivities have remained disappointingly low over the last decade, and are typically no better than 33% longward of 130 nm. MCP detectors are by far the most common devices in the ultraviolet. As photon counters, these devices have very low noise characteristics, which gives them a large advantage in background-limited astronomical observations, despite their poor sensitivity, see Table 1. They have low dynamic range and require high voltage, but can be operated at room temperature. They are unaffected over time by the radiation environment but have limited lifetime.

TABLE 1: *Present-day performance characteristics of selected flight detectors and potential future devices.*

	CCDs	CMOS Active pixel sensors	STJ/TES	MCP devices	EBCCDs	AlGaN
Performance						
Wavelength range	visible-uv	visible	visible-uv	solar-blind uv	solar-blind uv	solar-blind uv
DQE (%)						
FUV (130nm)	45 JPL			33	*50 CsI*	*60*
NUV (250mm)	58 WFC3			10 STIS	*30 CsTe*	*80*
Vis (600mm)	80	50	50	$< 10^{-6}$	*$< 10^{-6}$*	*$< 10^{-6}$*
Format (pixels)	4k x 2k: 2 butted	1k x 1k	2 x 2 TES 6 x 6 STJ	16k x 1k: 2 butted	320 x 256	256 x 256
Pixel size (µm)	15 x 15	7.5 – 15 sq	20 – 25 sq	6 x 30	30 x 30	25 x 25
Read-noise (e^- rms)	5	20 - 30	none†	none	5*	unavailable
Dark noise (cnts/sec/res el)	6.7×10^{-3}	high	0	$< 2 \times 10^{-5}$	$\sim 4 \times 10^{-6}$	$\sim 8 \times 10^{4}$
Global Dyn Rng (cnts/sec)			400k	21k	123k	
Local Dyn Rng (Cnts/sec/pix)			20k	8	45	
Full well	75k	300k				
Energy Resolution (at 400nm) (E/ΔE)	none	none	5 STJ 20 TES	none	none	none
Environment						
Radiation Hard	no	yes (1Mr)	yes	yes	yes	yes
Lifetime (cnts/mm^2)	radiation	radiation	coolant	10^{11}	10^{12}	radiation
High voltage	no	no	no	yes	yes	no
CTE	0.999995	n/a	n/a	n/a	n/a	n/a
Op temperature (°C)	-85	-85	0.1 - 0.3K	25	25	25
Power (w)	50††	0.01		40	20	
Readiness						
TRL	8	3	2	8	8	2

Explanatory Notes

Where possible, data are from present-day flight devices (or space-qualified). Entries in italics are predictions.

CCD: data are for ACS-WFC detector, except for DQE FUV (JPL delta-doping) & NUV (WFC3), as noted; lifetime determined by radiation environment
††power does not include flight operations and data handling
MCPs: data are COS-FUV detector, except for DQE NUV (STIS-MAMA)
EBCCD: based on IMAPS camera, except for predicted DQEs, as noted
* device used in analog mode
STJ/TES: †read noise is zero in photon counting mode; lifetime may be determined by coolant
CMOS: power value does not include cooling requirement
TRL: Technology Readiness Levels as described in Table 2

For both ultraviolet and visible light detectors there are specific parameters that need to be improved. Most importantly, focal plane area needs to be increased, as moving to larger formats increases the discovery space. The need for larger detectors is obvious for most imaging applications, especially observational cosmology, but high resolution or multi-object spectroscopy also places heavy demands on detector format.

Another critical parameter to improve is detector sensitivity, which implies a combination of increased quantum efficiency and reduced detector background. Improvements in QE are needed in the ultraviolet.

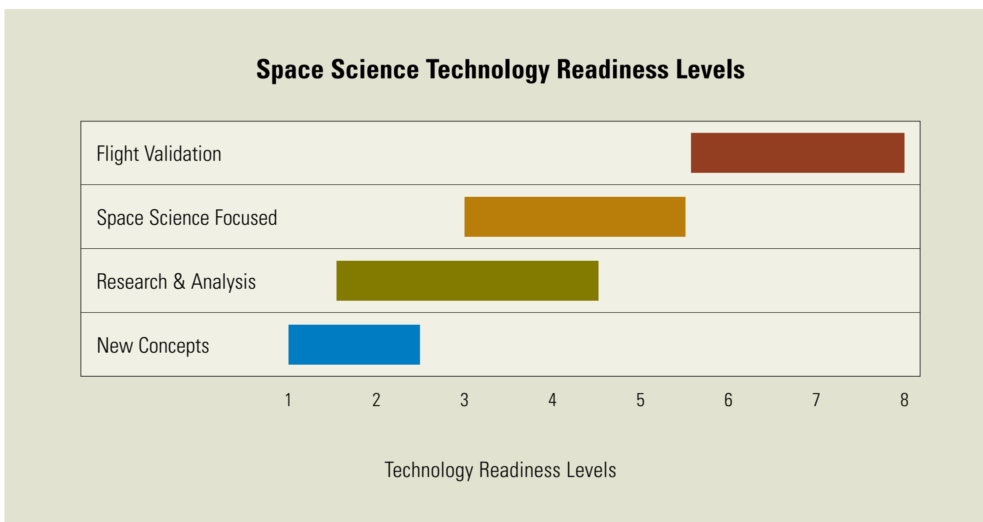
High dynamic range is important because typical astronomical images or spectra can contain very large ranges of pixel intensities. Good in-flight robustness is required.

A number of new detector technologies are close to providing substantial improvements across the range of performance characteristics. In the next section, this report discusses the various detector types and associated technologies, and identifies specific areas where improvements should be sought. The report follows the classification of Technology Readiness Levels (TRL 1 through 8) defined by NASA in its Space Science Strategic Plan for 2000 and illustrated in Table 2.

Definitions of Technology Readiness Levels

- **TRL 1** Basic principles observed and reported.
- **TRL 2** Technology concept and/or application formulated.
- **TRL 3** Analytical and experimental critical function and/or characteristic proof-of-concept.
- **TRL 4** Component and/or breadboard validation in laboratory environment.
- **TRL 5** Component and/or breadboard validation in a relevant environment.
- **TRL 6** System/subsystem model or prototype demonstration in a relevant environment (ground or space).
- **TRL 7** System prototype demonstration in a space environment.
- **TRL 8** Actual system completed and flight qualified through test and demonstration (ground or space).

TABLE 2: *Technology Readiness Levels, adopted from the NASA Space Science Strategic Plan, 2000.*



2 Solid-State Devices

2.1 Silicon Charge-Coupled Devices (CCDs)

Si CCDs are at the heart of most astronomical detection systems in use today at ground-based Observatories. These devices are thin silicon structures divided into pixel arrays by electronic circuits contained on the front surface. Photons that enter the device are absorbed, promoting electrons to the conduction band. These electrons are held against a barrier where they accumulate until they are read out by moving the charge through the structure to an amplifier at the edge of the array. The amplifier output signal is proportional to the accumulated photoelectrons in each pixel of the array; the amplifier signal is converted into an array of numbers proportional to the number of photons absorbed in each pixel, and a resulting image is produced.

CCDs provide many advantages as astronomical detectors, including the ability to integrate signal over long periods of time, high dynamic range, relatively low noise, high sensitivity at visible wavelengths, large focal plane sizes and excellent photometric stability. Developed approximately thirty years ago, CCD technology is mature and has become familiar to astronomers, a strength in their use as detectors.

For a comprehensive treatise on CCDs, see: Janesick, James, R. 2001. *Scientific Charge-Coupled Devices*. Bellingham: SPIE Press.

The Working Group received presentations from Mark Clampin, STScI, and Shouleh Nikzad, JPL, and these can be viewed online by following the links at: www.stsci.edu/detectors and from Stewart Collins and Mark Wadworth, JPL, and John Tower, Sarnoff.

2.1.1 HST CCDs

These devices have been used extensively in the Hubble Space Telescope (HST), from the original Wide Field Planetary Camera (WFPC) to the future Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3). The rise of the CCD to its current ubiquitous place in astronomy can be traced back, in part, to the original decision to select these new and largely unproven solid-state devices rather than SEC Vidicons for WFPC and the Voyager mission to Jupiter[1]. Future NASA missions, both in study and in proposal, are designed around CCD focal planes.

The HST program provides a rich base of information for remote CCD operations in a low-Earth orbit (600 km), including effects of the radiation environment on these devices. Five succeeding generations of CCDs have been used in a variety of HST's cameras. The CCDs in WFPC2 have been in use since 1994. Although they would not be considered state-of-the-art by today's standards, these detectors have nevertheless played a key role in obtaining many of HST's most significant results and have demonstrated their versatility from solar system studies to observational cosmology. The WFPC2 CCDs are front-illuminated devices and the polysilicon electrode structure on the front surface affects both the QE and MTF. The detectors have a peak sensitivity of ~40% at 700 nm, which is low by current standards, a read noise of 5 electrons/pixel (rms) and a dark current of 0.0045 electrons/second/pixel.

[1] Robert W. Smith and Joseph N. Tatarewicz, in *Replacing a technology: The large space telescope and CCDs*, 1985. Proceedings of the IEEE, 73, p1221, describe the debate over the choice of detectors for Hubble's chief imaging instrument. They present arguments that the rapid development of CCDs as astronomical detectors was due to a strong mix of "market pull" and "invention push" together with a strong scientific interest.

We think similar forces are present for the future technologies of CMOS APS and AlGaN devices.

A composite filter image of the spiral galaxy, M51, obtained using CCDs on board the Hubble Space Telescope. Acknowledgement: Hubble Heritage team, details at: http://heritage.stsci.edu

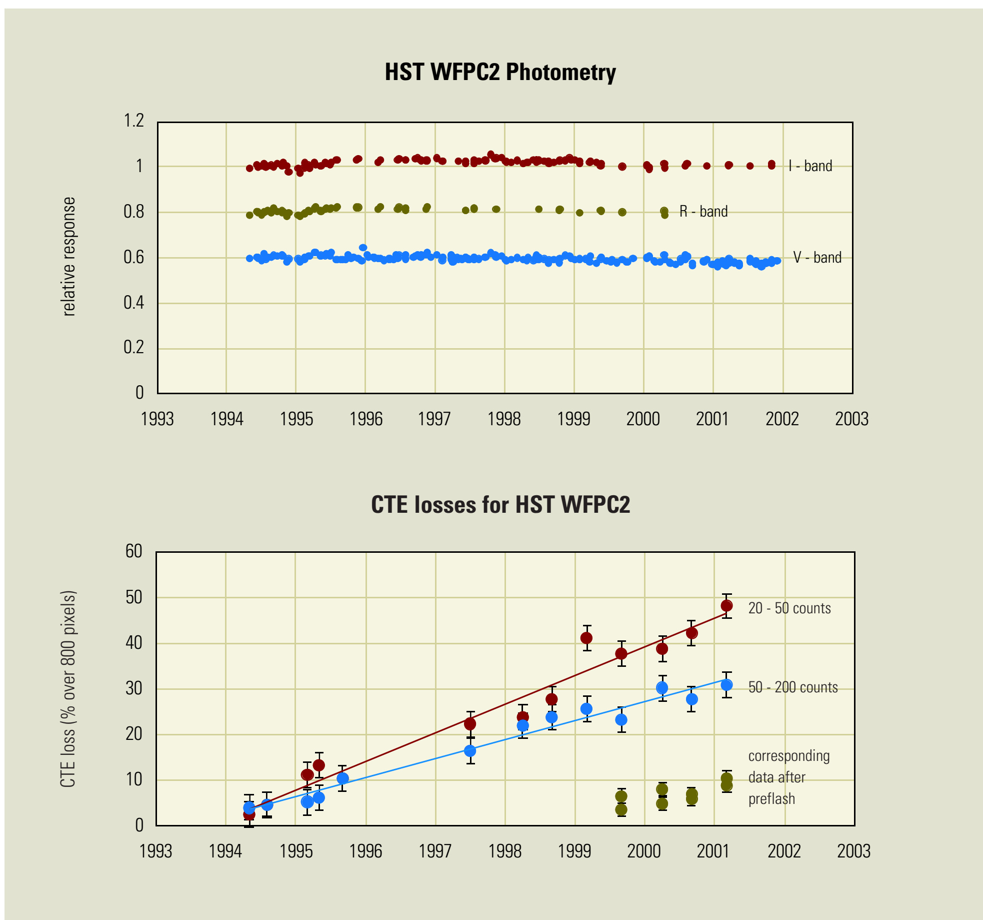
Recently, WFPC2 obtained its 100,000th image. Since 1994 the CCDs have demonstrated a high level of photometric and flat field stability. The instrumental throughput has been stable to ~2%, see Figure 1, except at the very faintest levels. However, the radiation environment has caused damage to the silicon, and this is manifest through:

I.) an increase in the numbers of hot pixels,
II.) a rise in the background level, and
III.) a degradation in the charge transfer efficiency (CTE), which is most discernable at low light levels.

2.1.2 CTE Concerns

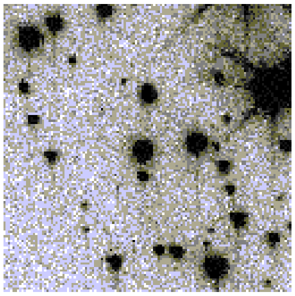
CTE—the fraction of charge successfully transferred per pixel transfer—is a fundamental aspect of CCD operations, and with careful design and chip selection can be made better than 0.999995. Defects or traps in the silicon can remove small amounts of charge from the charge packet as the accumulated charge is transferred from one pixel to the next during readout. These defects are created when high-energy particles such as protons, electrons, neutrons and heavy nuclei displace atoms in the silicon. Consequently, over time the radiation in space will degrade CTE of any CCD. The WPC2 CCDs now show CTE losses of over 50% for the faintest targets recorded on very low backgrounds due to radiation damage. The losses for bright targets are much smaller. (See Figure 1.)

FIGURE 1: *Different aspects of the WFPC2 CCD performance are revealed in these figures.*



The UPPER plot shows the overall photometric stability as determined by routine monitoring of the bright standard star GRW +70D5824. These observations, conducted since May 1994, indicate that the throughput for most filters has been stable to ~2%. The filters shown here are the I-band (F814W), the R-band (F675W) and the V-band (F555W).

The LOWER plot shows the CTE loss in percent over 800 pixels against time for two count levels, 20 – 50 counts [●] and 50 – 200 counts [●], and low background (worst case scenario) observed through the I filter. The loss is more than 50% of the incident flux. Preflashing the data gives a significant improvement in CTE, as indicated by the [●] data points. Details by Inge Heyer, John Biretta and colleagues, STScI, online at: www.stsci.edu/instruments/wfpc2/wfpc2_doc.html



CTE degradation can be seen in the image above. This is a small part of a larger 1k x 1k CCD image (HST-STIS), which is situated far from the readout amplifier. Charge moves up the page during readout. The tails of lost charge stream from the stellar point sources in a direction away from the readout amplifier. The charge from these stars has undergone ~1000 transfers and is showing the results of poor CTE (from Cawley, L., et. al., *HST CCD performance in the second decade: charge transfer efficiency*. 2001 Baltimore: STScI Publication).

There are ways to mitigate loss of CTE due to radiation damage. Careful screening and CTE testing is important in selecting flight parts with the best possible CTE at the outset. The use of a pre- or post-flash illumination capability within the camera can improve CTE by filling traps with a low level of signal: the CTE is improved (see Figure 1), but with the penalty of increased noise. HST ACS is planning a post-flash illumination. Another potential method is via charge injection, where charge is injected electronically into the CCD in individual rows. These lines of charge are clocked out ahead of the signal of interest. The charge acts like a pre-flash by filling in the traps, but since it does not interact directly with the signal of interest there is no associated shot noise. HST WFC3 is investigating the usefulness of this approach. During on-orbit operations, careful calibration and monitoring of CTE can be used for later correction in the data reduction process. Nevertheless, radiation damage remains a severe problem for long use CCD operations in space.

2.1.3 CCD Performance

Current CCD designs provide substantial advances over the WFPC2 devices. The present day, state-of-the-art in space qualified design is found in the CCDs for ACS, due for deployment with HST in 2002. These detectors are backside illuminated to provide high sensitivity. Backside processing involves thinning the substrate to the epitaxial layer, back-side passivation and the deposition of an anti-reflection coating. Sensitivities of various modern devices compared to the WFPC2 CCDs are shown in Figure 2, and the expected performance characteristics of the ACS CCDs are given in Table 1.

The visible and near ultraviolet sensitivities of these new devices are astounding. Lowering dark noise and reducing read noise have been harder to achieve, and improvements in these areas would be very worthwhile. For example, the read noise of the ACS CCDs is about the same as for the first generation of CCDs, despite a considerable effort to reduce this to lower values.

Read noise and dark noise should be improved, especially for regimes of low UV flux levels and low sky backgrounds, where CCDs can quickly lose out to the photon counting device's much lower background. The Skipper amplifier design and other potential methods to achieve sub-electron readout noise levels at MHz pixel rates have been proposed.

Figure 2: *CCD sensitivity curves.*

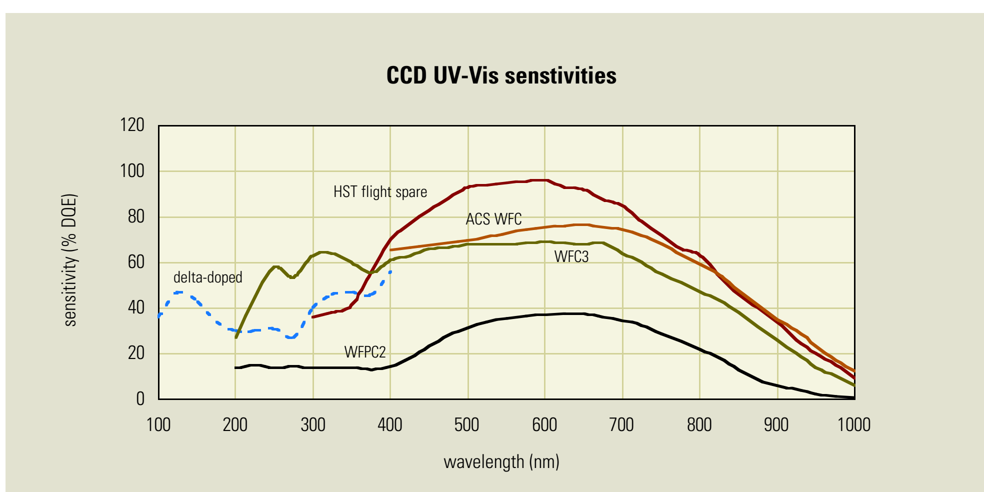


Figure 2 shows a selection of DQE curves (solid lines) for various flight CCDs in the HST program, including WFPC2, the ACS Wide Field Camera, a potential flight part for WFC3, and a flight spare. The dotted curve labeled delta-doped is adopted from data provided by Dr Shouleh Nikzad, JPL.

Improving the ultraviolet sensitivity of CCDs is an important development area. A number of companies, including Sarnoff, SITe, and Marconi, UK, are active in this area, as well as JPL and University of Arizona.

2.1.4 CCD UV Sensitivities

There are techniques to extend the sensitivity of CCDs into the ultraviolet, including phosphor coatings and backside processing. UV sensitive phosphors such as those employed on WFPC (Coronene) and WFPC2 (Lumogen) have achieved around 15% at wavelengths from 120 to 300 nm. Detecting UV photons with thinned CCDs requires careful passivation of the CCD backside by ion implantation or backside charging techniques. The STIS HST team developed a 1k x 1k device with a SITe near-UV backside CCD enhanced for 200 to 400 nm.

Delta-doping is another backside process for far UV imaging with CCDs. Using molecular beam epitaxy, fully-processed thinned CCDs are modified for UV enhancement by growing 2.5 nm of boron-doped silicon on the back surface. Named delta-doped CCDs because of the sharply spiked dopant profile in the thin epitaxial layer, these devices exhibit a good QE response in the ultraviolet (see Figure 2) and have been shown to be both uniform and stable over time. However, without efficient solar-blind filters (see Finding E), these UV enhanced CCDs are of limited use for most astronomical applications.

2.1.5 Future Requirements

There remain compelling needs for science grade CCDs for both ground and space applications. A few commercial companies remain interested in their production, although scientific CCD foundry capabilities can come and go on timescales of flight instrument procurement. A number of research centers continue to exploit the capabilities of CCDs. A new CCD architecture called orthogonal transfer (OT) has been developed, which permits interpixel charge shifting during integration. The OTCCD is intended for compensation of wavefront tilt in real time, but may also be suitable for specialized applications for space.

Using a spin-off of detector technology from high-energy physics, p-channel CCDs are being developed that are based on fully depleted p-i-n diodes fabricated on high-resistivity silicon. Conventional CCD processing is employed, but with high-resistivity starting material. A thin backside contact structure allows for rear illumination with good blue sensitivity, while the nominal 300 micron thickness yields good red and near IR response. Radiation hardness is expected to be good. Drawbacks include enhanced sensitivity to cosmic rays and background radiation.

Development priorities for future applications are given in Table 3.

Table 3: *CCD development priorities.*

CCD		
	Development priority	**Possible solution**
	Radiation hardness & CTE	p-type CCDs; charge injection techniques
	Larger formats	Mosaicing, multiple device packing
	Reduce read noise	New circuit designs
	Improve UV QE	Backside treatments

Future plans include space missions that require CCD imaging capabilities on a very large scale. FAME which had once been selected by NASA as a MIDEX mission for launch in 2004 was designed initially to employ 24 2k x 4k CCDs arranged around a 1.1 degree diameter field of view. The Kepler mission, designed to survey the solar neighborhood for planets, will employ 42 1k x 2k CCDs in its focal plane. Kepler has

CCD development milestone

been selected as a Discovery class mission for launch in 2006. SNAP is planned to have over 100 CCDs stitched together for its 1 square degree focal plane. SUVO has requirements for a large focal plane that operates at visible wavelengths. The European Space Agency has selected GAIA as a cornerstone mission with plans for an array of 276 astrometric and photometric CCDs.

These proposed cameras represent huge increases when compared with today's state-of-the-art in space-qualified design—a pair of 2k x 4k butted devices in ACS. Both the HST and FAME programs have found difficulty in obtaining science grade CCDs in the U.S. In the recent past, the manufacturing yield of quality CCDs that meet exacting science requirements has been very low. Furthermore, numerous packaging and processing issues that arise during construction of the focal plane cameras themselves conspire to reduce the final yield even further.

Access to vendors able to fabricate science grade CCDs remains a concern. The CCD manufacturing base, and especially a capability to develop science grade CCDs, is declining in the U.S. (The WFC3 program chose to go overseas to procure their flight CCDs.) This situation is bound to exacerbate development of the next generation of billion pixel missions, which will need vendors to meet large volume fabrication schedules at a time when industrial attention is turned to alternative technologies such as CMOS imagers.

There is a need to mitigate risk, contain cost and limit schedule growth by bridging the gap between laboratory proof-of-concept and flight readiness. This certainly applies when current CCD cameras are scaled up by factors of 10 to 100. Intermediate milestones in these development programs may be required.

We note also that detector technology requires maintaining a stable funding profile to protect the knowledge base and to keep expertise together. We need to pool and coordinate the experience and knowledge base acquired over the last decade to aid in the development of the future large focal planes.

2.2 CMOS Active Pixel Sensors

The section on CMOS Active Pixel Sensors is based around a presentation made to the Working Group by Bedabrata Pain, JPL, which can be viewed online by following the links at: www.stsci.edu/detectors and by Bill Weissband and Yibin Bai, Rockwell Science Center.

CCDs ARE BEING CHALLENGED by newer technologies that can provide improved radiation hardness, low power consumption and integrated camera systems. These technologies include CMOS Active Pixels Sensors (APS) and hybrid CMOS focal plane arrays. Although these devices are not yet close to matching the imaging performance of CCDs, in the future they may well offer the most practical approach for constructing very large focal plane arrays.

While CMOS visible imaging technology predates CCDs, the early devices operated with large temporal and spatial noise and were not suitable for large format implementation. These limitations resulted from the use of passive pixels. The situation changed in the 1990s with the widespread advent of sub-micron fabrication technology and an unchallenged predominance of CMOS very large scale integration (VLSI) consumer electronic devices that include cellular phones, televisions and personal computers. Sub-micron feature sizes enabled the use of active pixel concepts, setting the stage for the re-emergence of CMOS technology as visible imagers.

FINDING B
For space astrophysics missions in the future, APS technology offers advantages over CCDs and we encourage development of science quality APS devices. These advantages include:

- Low-power
- Ease of operation with a simple interface
- Random access (subarrays)
- Constancy of read noise with operating speed
- Excellent anti-blooming
- Large signal handling capacity
- Operation over a large range of temperatures
- Availability of smart features
- A high level of radiation tolerance

2.2.1 Advantages of CMOS APS

An active pixel refers to the incorporation of MOSFETs in the pixel that causes charge to a buffered signal (voltage or current) to occur at the pixel itself. This way, the need for charge transfer over a long bus (either through repetitive transfer or via charge sharing) is eliminated. Since the pixel is implemented in CMOS technology, unlike a CCD, an APS is capable of integrating not only the pixel array, but also the timing and control, digitization, interface control, and bias circuits in one chip—resulting in a compact, low-power camera-on-a-chip.

For CCDs, the controlling ancillary equipment is typically located on separate electronic boards and chips, making these systems bulky and power hungry. The Wide Field Camera in the ACS dissipates up to 27 watts and the support electronics for both ACS CCDs dissipates nearly 200 watts. Furthermore, CCDs require specialized silicon processing which is incompatible with CMOS technology. CCDs are high capacitance devices, requiring multiple non-standard and high voltage clocks and biases, while providing only serial output through repetitive charge transfer, precluding random access to pixels.

2.2.2 CMOS APS Improvements

There are important performance aspects that must be improved to allow entry of CMOS imagers into astronomical applications and to make them truly competitive with CCDs. First, the format size needs to be increased. High quality 1k x 1k devices are becoming available, and 10 Megapixel devices are expected to be available within the next two years. Larger format devices will require reticle stitching, a service provided by most advanced CMOS foundries. For billion pixel imagers, new buttable architectures with efficient methods for extraction of focal-plane data are needed.

The dark noise needs to be reduced, which can be a factor of a hundred higher than for CCDs. Solution to the problem includes passivation implants at STI (Shallow Trench Isolation) edges, low-energy implants for the device layer (i.e. the well), and additional surface implants. In this connection, an imager implemented in SOI (Silicon on Insulator) technology may provide a significant advantage, since the photodiode is placed in a planar region, enabling easier application of passivation implants. Lastly, newer pixel designs with lower perimeter voltages will also help the situation significantly.

The read noise needs to be reduced. At present, APS read noise is ~20-30 e^-/pixel at room temperature. New circuit techniques are becoming available for beating the fundamental kTC noise limit to provide CMOS imagers with one electron or sub-electron read noise. Fixed pattern noise is also a problem with APS devices. The solution may require a mixture of on-chip circuit techniques and off-chip calibration to reduce fixed pattern noise below read noise limits.

Linearity of these devices needs to be improved. There are two linearity components: overall and lower light level. Use of analog column circuits allowing the imager pixel to be reset in flushed reset (preset followed by soft-reset) can provide excellent low light linearity, low noise (2x lower), zero image lag and largest dynamic range. Improvement of linearity over the entire signal range can be obtained by appropriate signal chain circuit design and through advanced processing techniques to improve diode linearity.

Both the DQE and MTF can be increased by appropriate choice of epitaxial silicon doping and thickness. Highest DQE and MTF are achieved either by using thinned and backside illuminated CMOS pixels or by using a hybrid p-i-n detector approach. While both approaches are technically viable, it is unclear at the present time which one will prove to be the more reliable.

CMOS development milestones

1k square device with good performance to TRL 7
Mosaic ~10^8 pixels to TRL4

These areas require a sustained research and development effort in the coming decade. However, in the drive to ever larger focal planes and increased numbers of pixels, solving these problems will be important in order to support the next generation of billion pixel images in space. Development priorities are given in Table 4.

TABLE 4: *CMOS APS development priorities.*

CMOS		
	Development priority	**Possible solution**
	Reduce dark current	Passivation implants, new pixel designs
	Reduce read noise	New circuit designs
	Larger formats	Stiching designs
	Improve linearity	Signal chain circuit design
	Improve UV-Vis QE	Backside treatments

2.2.3 FUTURE ACTIVITIES

It is important to gain experience with CMOS APS technology in space missions. A small CMOS APS device flew as one of the MICAS detectors on board the highly successful and innovative spacecraft Deep Space One. DS1 recently flew by Comet Borrelly, obtaining unique imaging and spectroscopic data. Further flight opportunities should be sought. A CMOS APS needs to be developed to TRL 7 with a 1k or 2k square format for use in a Midex or Explorer class astronomy mission, and the feasibility of stitching arrays together to form a very large focal plane needs to be demonstrated to TRL 4.

CMOS imagers can also be used as readout elements with other technologies. In hybrid applications, for example, bump-bonding can be used to couple CMOS circuitry to a CCD-based imaging array, and methods of coupling MCPs to CMOS circuitry for UV imaging are also being investigated.

The main propellant that fuels the growth of CMOS imagers is the ubiquitous presence of CMOS VLSI and an emerging consumer market far beyond conventional camcorder applications. Although CMOS imagers developed for consumer applications are not directly applicable to scientific applications, NASA is in a good position to exploit the huge CMOS fabrication infrastructure to develop CMOS imagers suited for its use. There are economically driven opportunities to form collaborative relationships with imager chip manufacturers and with the foundries themselves; foundries that service the commercial sector may be willing to fine tune fabrication processes to suit NASA's needs.

TABLE 5: *A challenging but plausible development roadmap for CMOS APS devices.*

Development Roadmap for CMOS APS Devices					
Year	**1999**	**2000**	**2001**	**2002**	**2010**
Format	0.25M	1M	4M	16M	1000M
QE (percent)	40	50	80	90	90
Noise	50	25	10	5	<1
Digitization	8	12	12	12	20
Full-well	200k	200k	200k	500k	1M
Rad. Hard	25kR	1MR	1MR	1MR	10MR

Finding C
The sensitivity of ultraviolet solar blind detectors needs improvement. AlGaN detectors promise huge sensitivity improvements in the ultraviolet. Although research is still in its infancy, we encourage a vigorous development effort to create ultraviolet image sensors out of these materials.

2.3 GaN and AlGaN Devices

Future solid-state detectors made from Gallium Nitride or Aluminum Gallium Nitride materials have the potential to become the detector of choice for most ultraviolet applications. (We shall use AlGaN to refer to both GaN as well as the AlGaN alloys.) In contrast to silicon CCDs which have an energy gap of 1.1 eV to promote an electron to the conduction band, AlGaN is a wide-band gap material (3.4 eV for GaN to 6.2 eV for AlN), making the AlGaN detector inherently solar-blind. It should be operable at room temperatures without thermal backgrounds and should be radiation hard. Similar to other solid-state devices, AlGaN detectors will be lightweight, compact, and can record photons at very high rates. Solid-state devices, unlike photo-emissive devices, do not require high voltages and thereby avoid one inherent reliability risk.

In the periodic table, GaN and AlGaN are members of the Group III-Nitride (Group III-V) elements. As an opto-electronic material, AlGaN appears to hold greater promise than other wide bandgap materials such as diamond or SiC because Group III-V has direct electron transitions. For ultraviolet detectors in particular, AlGaN offers the following advantages over other materials:

i.) a higher absorption coefficient,
ii.) a sharper cut-off of the red tail,
iii.) a higher response speed, and
iv.) the possibility of making hetero-junction devices.

The section on AlGaN devices is based around presentations by Chuck Joseph, Rutgers, Brent Mott and Ted Huang, GSFC, Marty Peckarer, NRL and Ian Fergeson, Emcore.

For AlGaN DQE measurements see: www.physics.rutgers.edu/ast/uvlab-results.htm

2.3.1 UV Sensitivity

AlGaN detectors promise huge sensitivity improvements in the ultraviolet. Theoretical DQEs for AlGaN are shown in Figure 3, where they are compared with current values. Such very-high UV detective quantum efficiencies (DQE ~ 85%) are expected to be stable during long term space applications because condensable contaminants do not form on a warm surface. The material does not form oxides or have other surface chemistry that adversely impacts the short wavelength efficiencies. The high sensitivity, coupled with an inherent solar-blindness ($<10^{-7}$ at 400 nm), is a feature that makes AlGaN exceptionally interesting as an ultraviolet detector.

Several groups have already demonstrated laboratory AlGaN DQEs in excess of 60%. During the Detectors Conference, a number of papers were presented that described promising results from prototype AlGaN detectors, and the reader is referred to these papers and the selected bibliography at the end of this report for full details. A variety of p-i-n photodiode arrays, of sizes from 32 x 32 to 256 x 256 pixels, have been successfully constructed. These arrays have been hybridized to Si readout integrated circuits using Indium bump-bonding techniques and inserted into specially designed cameras to produce ultraviolet images.

FIGURE 3. *A comparison of sensitivities for a variety of solar-blind devices.*

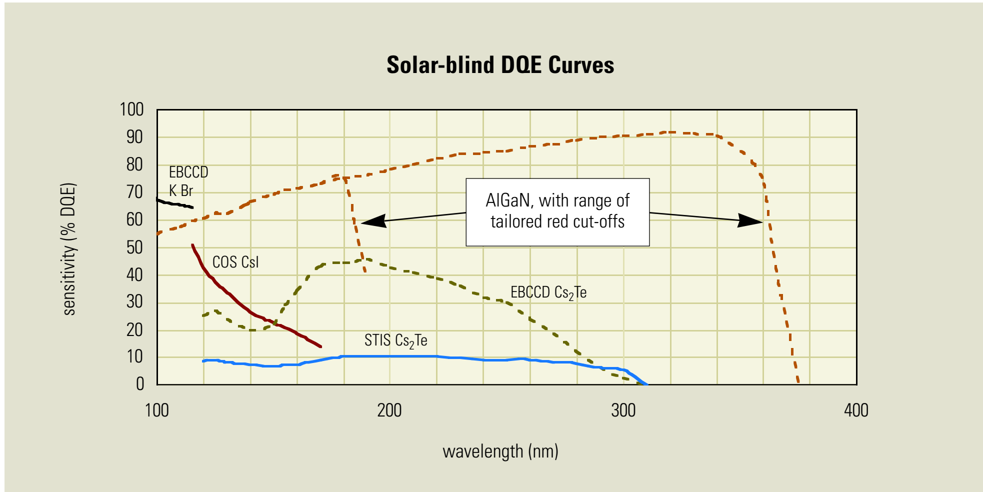


Figure 3 shows a number of sensitivity curves for solar-blind detector types. Solid curves denote flight detectors for: IMAPS, an EBCCD detector with an opaque KBr photocathode; HST-COS, an MCP detector with an opaque CsI photocathode; and HST-STIS, a MAMA NUV detector with a semi-transparent Cs_2Te photocathode. Dotted curves are predicted sensitivity responses for AlGaN and a sealed-tube EBCCD with an opaque Cs_2Te photocathode. Note that higher QE is always obtained for an opaque rather than a semi-transparent photocathode treatment.

2.3.2 Material Defects Associated with AlGaN

The primary challenge to overcome before AlGaN detectors are useful for UV astronomy is to reduce the very large non-thermal background produced by material defects. Currently, high quality n-doped AlGaN materials are readily available and sensors with good DQE have been realized. The full potential of AlGaN for use as an ultraviolet imager, however, cannot be realized until good p-doped GaN materials become available. While p-doped GaN has recently been created and the quality of the material is improving rapidly, substantial research is required to reduce the density of traps and defects. Other issues facing the material scientist include extending the range of dopant levels and metalization, i.e.: making good ohmic connections to the GaN.

Most AlGaN device development programs have fabricated photoconductive (PC) structures, which have had good UV sensitivity, but also have very high leakage currents (dark signals in the absence of an incident flux). These unacceptably high dark signals are the direct result of the defects, especially dislocations that tend to thread from one wafer face to the other. PC structures in which the electrical transport normally runs parallel to the wafer face encounter more of these dislocations than do photovoltaic (PV) structures, where the electrical transport is normal to the face.

AlGaN development milestone

256 x 256 array with good performance to TRL 7

2.3.3 Future Prospects

Gallium Nitrides are expected to play a major role in numerous strategic technologies such as light-emitting diodes (LEDs), high power, high frequency microwave devices and teraflop computing and image sensors. GaN LEDs are being developed to produce 120 lumen/watt light bulbs that will result in large energy savings. Teraflop computers and UV image sensors are considered by the Department of Defense to be strategic technologies, with GaN materials playing a critical enabling role. The inherent advantage of having a direct bandgap for UV detectors and other devices can be seen in the breadth and scale of GaN research being conducted by government laboratories, universities and corporations in the United States and elsewhere.

While AlGaN devices have the potential to be superb UV detectors, the technology is still in its infancy and requires substantial, prolonged development. Fortunately, there is a huge commercial and military interest in this material, including the desire for a solar-blind UV image sensor. Tremendous strides have been made in recent years to reduce the defects and dislocation that cause these unwanted backgrounds. NASA can leverage off the enormous worldwide investment being made in GaN materials research to develop UV image sensors that meet NASA's unique set of requirements.

GaN and AlGaN detectors promise huge sensitivity improvements in the ultraviolet. Accordingly, we encourage a vigorous device development effort to create UV image sensors out of these materials, leveraging off the enormous worldwide investment being made in GaN materials research. The primary challenge to overcome before GaN detectors are useful for UV astronomy applications is to reduce the very large non-thermal background produced by material defects. High priority development tasks are given in Table 6. Developing a low noise 256k square device to TRL 7 in the next five to seven years would be a very worthwhile goal.

Table 6: *AlGaN development priorities.*

AlGaN	Development priority	Possible solution
	Lower backgrounds	Material quality
	Larger formats	Device structures

3 Superconducting Devices

FINDING D
We anticipate that superconducting detectors like the Superconducting Tunneling Junctions and the Transition Edge Sensors will be important detectors for space astrophysics applications in the long run because they provide simultaneous broad-band imaging, time tagging and high-efficiency, low-resolution spectroscopy.

3.1 STJ and TES Time & Energy Resolving Detectors

AN IDEAL PHOTON DETECTOR would absorb each photon while providing maximal information, including xy image position, arrival time, energy and polarization. For the past fifteen years, such detectors operated below 0.1 K have been available in the x-ray band, where the combination of high resolving power (now R~1500 at 6 keV) and high efficiency (~100% at 6 keV) make them the detectors of choice for the next generation of x-ray satellite missions such as Astro E2 and Constellation X. These detectors are based on superconducting tunnel junctions (STJ) and microcalorimeters, which use semiconducting thermistors and superconducting transition edge sensors (TES).

Over the past decade, the STJ and TES cryogenic technologies have been extended to access longer wavelengths in the UV, visible and near IR. These detectors count single photons, while time-stamping to better than 0.1 μs and energy resolving with an attainable R~ 100 $(\lambda/100\ \mathrm{nm})^{-1/2}$. The same single photon counting cryogenic technologies scale from the near IR to the far UV and on up to x-rays. These same technologies, used with bolometric detectors, are the technology of choice at longer wavelengths for the next generation of CMB satellites such as Planck, Herschel (formerly FIRST) and ground based IR cameras such as SCUBA. In the visible through UV, the detectors have an absorption efficiency above 50%, and with coatings may approach 100% from the near IR through the UV.

The Working Group received a number of presentations on superconducting device technology, including Transition Edge Sensors (Blas Cabrera and colleagues at Stanford, and Sae Woo Nam, NIST), Superconducting Tunneling Junctions (Dan Prober, Yale), Kinetic Inductance Quasiparticle Sensors (Jonas Zmuidzinas, Caltech), and RF-SET detector readouts (Rob Schoelkopf, Yale, and Tom Stevenson and colleagues, GSFC). Details of these presentations can be viewed online by following the links at: www.stsci.edu/detectors

3.1.1 Energy Resolution

STJs are like semiconductor diode detectors, since the signal is proportional to the number of electron-like excitations produced by the photon. The difference is that the energy per excitation is less than a meV rather than about one eV, allowing a factor of ~30 improvement in the fundamental resolution. TESs, on the other hand, are calorimeters that actually measure the temperature rise in an isolated heat capacity to determine the photon energy. Their fundamental resolution (R) is inversely proportional to the square root of the transition temperature. As shown in Table 7, the fundamental resolution between TESs and STJs is remarkably similar. The noise from the counting statistics for the STJs, where the unit energy scale is given by kTc, ends up nearly identical to the noise from the thermodynamic fluctuations of the TESs with the same energy scale given by kTc. The one difference is that for a given STJ detector, the energy resolution is proportional to the square root of the energy, so that $R \sim E\gamma^{1/2}$, whereas for a given TES detector, the energy resolution is a constant given by the saturation energy, so that $R \sim E\gamma$.

TES

$$\Delta E_{FWHM} = 2.355\sqrt{4k_B T_e^2 C\sqrt{\tfrac{n}{2}}/\alpha}$$

$n = 5$ electron - phonon coupling

$T_e \approx T_c$ and $E_{sat} \approx T_c C/\alpha$

$$\Delta E_{FWHM} = 2.355\sqrt{6.4 k_B T_c E_{sat}}$$

$$\Delta E_{FWHM} \approx 15 \text{ meV} \left(\frac{E_{sat}}{1 \text{ eV}}\right)^{1/2}\left(\frac{T_c}{70 \text{ mK}}\right)^{1/2}$$

STJ or L_K

$$\Delta E_{FWHM} \approx 2.355\sqrt{E\varepsilon_0(F+G)}$$

$\varepsilon_0 \approx 1.7\Delta \approx 1.7(1.76 kT_c) = 3kT_c$

$F \approx 0.2$ is Fano; $G \approx 0-2$ (tunneling noise)

$$\Delta E_{FWHM} \approx 2.355\sqrt{0.6kT_c E}$$

$$\Delta E_{FWHM} \approx 18 \text{ meV} \left(\frac{E}{1 \text{ eV}}\right)^{1/2}\left(\frac{T_c}{1 \text{ K}}\right)^{1/2}$$

TABLE 7: *Comparison of fundamental resolutions for TES and STJ photon detectors.*

3.1.2 STJs or TESs?

The choice between STJ and TES will come down to which technology:

i.) most closely approaches the fundamental energy resolution limits,
ii.) provides the highest manufacturing yield and ease of operation, and most importantly,
iii.) can implement the largest pixel arrays.

With respect to the first question, both technologies have approached 0.15 eV FWHM near 1 eV (1.24 µm) and improvements of a factor of 2 or 3 are expected. Both technologies have demonstrated counting rates above 10 kHz per pixel. With respect to the second question, the critical fabrication issue is the control of Tc, which is more straightforward than the control of the tunneling barrier for the STJ, but is not a major advantage.

Both technologies must operate below 100 mK, but the cryogenic x-ray and CMB missions are already working hard on satellite cryogenic systems in this temperature range. With respect to the third question, the current TES technology has an advantage, because a time domain multiplexing technique has been demonstrated which takes advantage of the SQUID readout low noise. Recently, an interesting frequency domain multiplexing scheme has been suggested which utilizes a new low noise amplifier called the rf set (single electron tunneling). Also, a new readout scheme based on kinetic inductance in superconductors has the same fundamental resolution limits as STJs, but has an attractive frequency-domain multiplexing scheme that utilizes existing GHz room temperature electronics. Ultimately, large arrays will be key and the technology allowing the most straightforward path to large arrays will be chosen.

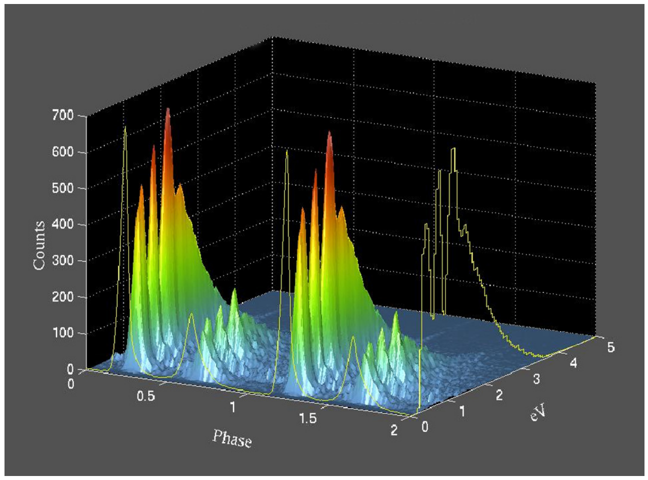


FIGURE 4: A simultaneous optical and near-IR time-resolved spectrum of the Crab pulsar obtained using a transition edge sensor spectrophotometer (Romani, R.W., et al 1999).

Superconducting development milestone

3.1.3 ASTRONOMICAL APPLICATIONS

Excellent astronomical applications for TES or STJ detectors are fast time variable sources such as pulsars, and neutron star and black hole binaries. Already, these point-source spectrophotometers have been used in ground-based observations of the Crab pulsar (see Figure 4) as well as several white dwarf, neutron star and black hole binaries. In addition, their high efficiency over a broad band make them good candidates for photon starved applications such as faint galaxies, where direct redshift measurements would be possible to 28 Mv with 10 meter class telescopes.

An interesting application would be a combined x-ray and optical-UV mission, where the cryogenics would already be provided for the x-ray detectors and simultaneous observations of point-like compact or faint objects would substantially advance the science. It is again important to note that the x-ray and CMB satellite missions, where cryogenic detectors must be used, will provide a space qualified infrastructure for cooling and electronics.

Due to their broadband nature, these detectors are not intrinsically solar-blind, and so do not easily replace the need for microchannel plates in the ultraviolet. The filters required to make them solar-blind, such as Wood's filters, have proven difficult to make with throughput efficiency better than 15%. Finding E in this report calls attention to the need for more efficient UV transmitting filters for use with superconducting devices; these filters must block IR and visible light. However, lower backgrounds than MCPs may be possible and may offset the filter efficiency for some applications.

Finally, a hybrid detector with a dispersive element, where all orders are allowed to hit a cryogenic array, would allow order sorting using the intrinsic low resolution of the detector and broadband through the simultaneous detection of 6 or 7 orders, each covering more than a factor of two in wavelength or energy. However, the order sorting for UV applications would need to be adequate for this to be a useful application of these devices.

3.1.4 Current and Future Prospects

With respect to arrays, the state-of-the-art for STJs is the imaging 6 x 6 European Space Agency camera, demonstrated at the William Herschel 6-meter telescope. An R~5 was obtained from 300 to 600 nm and was probably limited by infrared leakage. A 2 x 2 TES array has been built by Stanford/NIST and was fiber-coupled for observations at McDonald Observatory. An R~20 was achieved over a broadband from 1.7 µm to 350 nm. ESA is building an imaging 8 x 8 STJ array. Stanford/NIST are building an imaging 8 x 4 TES array, and Yale/GSFC are developing a 10 strip STJ array to provide 450 pixels with only 20 readout channels. These devices will be very useful for ground-based demonstrations where the atmospheric dispersion and guiding errors for point sources are completely contained within the array and nearby background subtraction is possible.

In the five to ten year timescale, we expect TES arrays in the 32 x 32 range with some multiplexing and STJ arrays utilizing one FET per pixel. These instruments should be considered for long duration balloon and sounding rocket observations and plausibly for SMEX and MIDEX missions. An interesting intermediate step to larger arrays would be a 1024 x 1024 array in which any 256 pixels could be addressed and read out continuously, much like a programmable multi-fiber spectrometer. The redshifts of a faint field such as the HDF could then be rapidly determined. Such an instrument would attack many of the fabrication issues for larger arrays, including buried wiring layers and high efficiency. There are no concrete designs to build 256 x 256 or larger arrays, but there are a number of interesting ideas that will be developed. In addition to the SQUID based time-domain multiplexing, these include frequency-domain multiplexing with rf set amplifiers for STJs and a new kinetic inductance readout scheme.

Clearly, these devices are in their infancy and many technological challenges remain before they can be considered viable UV-Vis detectors. It remains to be established whether they can be effectively multiplexed while preserving their dynamic range. However, research and development is active on these devices and they are being considered for space missions at other wavelengths. The major development priorities are listed in Table 8.

Table 8: *Superconducting detector development priorities.*

STJ/TES		
	Development priority	**Possible solution**
	Larger formats	Multiplexing, programmable image plane
	Blocking filters	Solar blind filters, grid filters
	Increase efficiency	Absorptive coatings
	Cryogenics	Technology developments

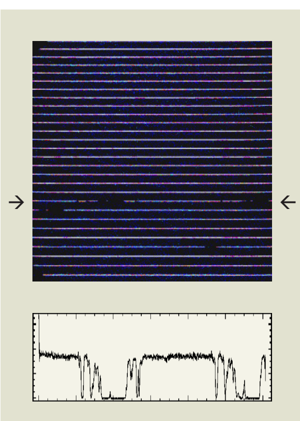
4 Photo Emissive Devices

Presentations to the Working Group on MCP developments by Oswald Siegmund and colleagues, UC Berkeley, can be viewed on line by following links at www.stsci.edu/detectors

4.1 Microchannel Plate Detectors

The MCP detector, with its long heritage of flight missions, is currently the workhorse detector for ultraviolet space astronomy. The flight heritage for MCP type detectors is strong and includes past missions like EUVE, ORFEUS, FAUST, and ALEXIS, and current missions HST/STIS MAMA, FUSE, IMAGE, SOHO and ACE. They are also baselined in missions under development—CHIPS, GALEX, TIMED and HST/COS.

MCP detectors consist of a plate of fine-pore glass tubes with a photocathode at the top surface. An ultraviolet photon incident on the photocathode releases a primary electron, which is accelerated down the MCP pore by an applied high voltage. The accelerated primary electron interacts with the glass pore walls, releasing secondary electrons. These secondary electrons similarly interact with the glass, releasing additional electrons so that the charge is multiplied into a detectable electric signal (with a gain of 500,000-1,000,000e^-). At the anode plane the exiting charge cloud is collected and its position determined by a readout anode structure that is customized to the detector application.

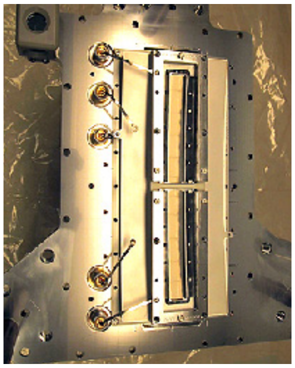


Echelle spectra obtained using the STIS near-UV detector on board the Hubble Space Telescope. One echelle order (arrowed) is extracted (line plot) to illustrate how much spectral information is available.

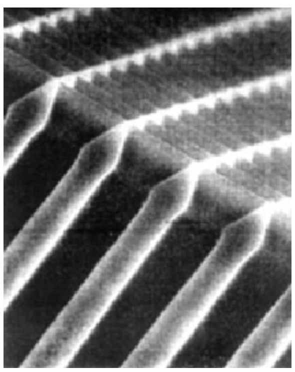
4.1.1 MCP Usage

MCPs have several strengths. They are robust in flight, radiation hard and normally employ solar-blind photocathodes. In addition, they operate at room temperature, can accommodate high-count rates and permit good timing resolution. They also have disadvantages: they require high voltage (~2 - 5 kV) and protection of the photocathode against exposure to moisture. They exhibit relatively low DQE, and fabrication of reliable detectors is a low yield process. (This latter difficulty is partially compounded by the small number of vendors of MCP glass worldwide.) In addition, MCP gain can be permanently depressed in regions of the plates exposed to high cumulative doses. In considering questions of dynamic range, it is known that in regions where local count rates are high, gain (temporarily) sags and detection efficiency drops.

The two ultraviolet HST/STIS detectors consist of curved-channel microchannel plates, utilizing a CsI photocathode on the front surface for the far-UV and a Cs_2Te photocathode coated on the inside of the detector window for the near-UV. Both detectors are permanently sealed tubes with MgF_2 entrance windows. Each detector incorporates a 1024 x 1024 element anode array. The devices have proven to be robust and reliable in the radiation environment of HST and are capable of yielding excellent signal to noise ratios (50:1 to 100:1). For HST/COS, the MCP far-UV detector is an open window, 3 channel stack based on the FUSE spacecraft detector design.



The COS XDL far ultraviolet detector, courtesy Oswald Siegmund, UC Berkeley, and Jim Green, U. Colorado.



Micromachined microchannel matrix for a precision Si-MCP fabricated at NanoSciences Corporation. The square channels are on a 6 micron spacing with a side dimension of 3 microns. Top surface micromachined to a tapered blade point to enhance collection efficiency, see Beetz, et al (2000).

We have identified a number of areas where improvements can be made to MCP detectors, including the plates themselves, the photocathode materials and the anode readout designs.

4.2 Glass and Si-Micromachined Microchannel Plates

The manufacturing yield of science grade glass MCPs is often very poor, and the processes involved require close attention to detail and excellent liaison between manufacturer and instrument builder. Further, there are very few companies either capable or interested in making high quality plates for astronomical uses. These serious drawbacks drive up development cost.

NASA is funding a new technology for Si-micromachined MCPs that holds great promise for the future. In this technology, MCPs are fabricated from standard silicon wafer substrates using a novel micromachining process in combination with standard silicon photolithographic processes to produce MCPs of exceptional precision and absence of defects.

These Si-micromachined MCPs appear to have many advantages over their conventional drawn-glass counterparts: they have no multifiber boundaries or array distortions, and are scalable to large sizes with small pores. In addition to desirable cosmetic improvements in MCP uniformity, reproducibility, and lack of defects, the Si-MCP technology holds the promise of major advances in sensitivity through improvements in both quantum efficiency (which remains poor when compared to achievements in the optical) and detector background. However, we note that Si-MCPs require better gain before they become viable as replacement for glass MCPs.

Silicon MCPs do not leach out reactive chemicals and can be baked at very high temperatures. They should offer a hospitable substrate for high efficiency photocathodes made of novel negative-electron-affinity materials; these detectors will enable significant sensitivity improvements. Similarly, the lower background of Si-MCPs (due to the absence of the radioactive materials found in glass MCPs) should offer significant sensitivity advantages in long, background-limited observations as well. Silicon microchannel plates of 25 mm diameter with 8 micron pore spacing are currently being produced, and we encourage efforts to develop large area Si-MCPs to TRL 6 as replacements for traditional glass MCPs.

4.3 Photocathodes

Improvement in photocathodes is a high priority goal for microchannel plate development. A few of the photocathodes are discussed below:

4.3.1 Alkali Halides

Alkali halide photocathodes are in common use (i.e., CsI, KI, KBr) with microchannel plate detectors. They have good QE, especially in the EUV and FUV range, i.e. from 30 to 150 nm, but cut off longward of 200 nm. These photocathodes require special handling to protect them from exposure to moisture. In addition, they can develop some visible light sensitivity after exposure to UV or ions and may be susceptible to degradation under UV irradiation.

We are grateful to Anton Tremsin (Berkeley), Tim Norton (GSFC) and Mel Ulmer (Northwestern) for presentations on photocathodes to the working group.

4.3.2 Diamond

Polycrystalline diamond films have wide (5.47 eV) band gaps and are solar-blind. These films are chemically stable (i.e. to alcohol and water), mechanically robust and appear to be stable with exposure to air. Hydrogenated diamond surfaces exhibit negative electron affinity, increasing their quantum efficiency and extending their cutoff to 200 nm. (Cesiated diamond surfaces are also expected to have negative electron affinity, but the photocathode must then be maintained in vacuum.) Most deposition techniques for diamond require high temperature, which is inappropriate for conventional MCP glass. However, diamond films could be deposited on Si-MCPs, which can sustain higher process temperatures.

4.3.3 Cs_2Te and RbTe

RbTe peaks around 100 nm, cutting off around 300 nm. Cs_2Te peaks (~40% for opaque PCs) around ~200 nm and cuts off at ~320 nm. Opaque depositions have higher QE than those that are semi-transparent.

4.3.4 AlGaN

AlGaN photocathodes are of interest because their theoretical QE curves are flat at about 50% with a sharp cutoff around 360 nm, depending upon the alloy mixture. The feasibility of using an AlGaN photocathode in conjunction with Si-MCPs for the near ultraviolet should be explored.

4.4 Anode Readouts

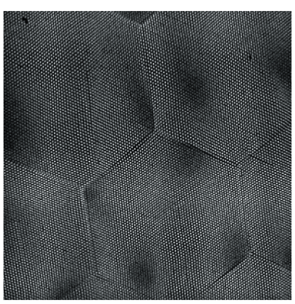


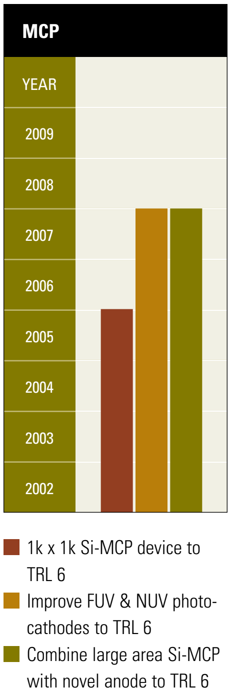
Image of a 2 mm x 2 mm section of the cross strip MCP detector showing the MCP hexagonal multi-fibers, individual pores, and patches due to moire interference. Courtesy Ossie Siegmund, Berkeley.

A LARGE NUMBER OF IMAGING readout schemes have been used in the past. Examples include various delay line anodes that were used in ORFEUS, SOHO and FUSE. Here the MCP charge cloud is deposited on upper and lower charge collectors, and the event position is determined by differences in signal arrival times at the ends of the delay line. Delay line anodes will be used on CHIPS, GALEX and HST/COS.

Readout schemes that employ charge measurement or charge comparison have also been flown. Continuous type anodes include the wedge-and-strip on EUVE and IMAGE and the resistive anode readout system on the Wide Field Camera of ROSAT. Discrete anode structures detect the photo-event location directly. Compared to continuous encoders, discrete anodes use significantly more amplifiers and achieve much higher local dynamic range. These devices include the Multi-Anode Microchannel Array (MAMA) (used in HST/STIS) and the capacitive readout system of the Coded Anode Converter (CODACON). A CODACON is used on TIMED.

These various schemes have particular merits, but none has yet achieved a distortion free system with position resolution sufficient to resolve MCP pores and accommodate large formats, small volumes and low power electronics. Thus, readouts continue to be proposed and developed beyond the current flight heritage, with design requirements driven by the specific detector application. Examples include the vernier anode (a continuous type anode) and the cross strip anode, a discrete system which employs centroiding of the charge cloud spread across multiple collecting strips. Analogous centroiding techniques have been successfully exploited in the X-ray band, most recently with the Chandra HRC. This represents an example of fertile exchange between wave-bands, which benefits detector development.

MCP development milestones



We encourage development of a prototype MCP detector to TRL 6 that combines a high-resolution readout scheme with large-area Si-MCP. Such a detector would be extremely powerful in the ultraviolet and would represent substantial gains over existing technologies. It should be achievable in the near future. We list important development priorities in Table 9 below.

TABLE 9: *MCP development priorities.*

MCP	
Development priority	**Possible solution**
Increase UV QE	New photocathodes, and Si-MCP
Develop Si-MCPs to full potential	Improve gain
Improve resolution	New readout designs

5 Hybrid Devices

EBCCD development milestone

HYBRID DEVICES ARE COMMON, especially in the ultraviolet. The very successful detectors onboard the IUE satellite (International Ultraviolet Explorer) are a good example of hybrid design. The basic detector was a UV-to-visible image converter coupled to a secondary electron conduction (SEC) television camera, sensitive to visible light only. These detectors performed reliably over many years of IUE operations.

Below we describe a few examples of hybrid detectors that offer excellent potential in the future.

5.1 Electron-Bombarded CCDs

ELECTRON-BOMBARDED CCDs (EBCCDs) for use in the far UV have been under development for a number of years. One such device with an opaque photocathode has been used in the IMAPS sounding rocket, which twice flew piggyback on the ORFEUS Mission. Another EBCCD flew on the Global Imaging Monitor of the Ionosphere, an Air Force orbital mission.

The EBCCD detector consists of a photocathode on a smooth surface, an accelerating electrostatic field of several thousand volts to accelerate the photoelectrons, and a thinned, backside illuminated CCD operated in frame transfer mode. A photoelectron striking the CCD produces approximately one secondary electron for every 3.6 eV of incident energy. In practice, each photoelectron produces approximately 3,000 electron-hole pairs. Each photo-event is localized in a width having an exponential (rather than Gaussian) spread with a scale length of 4-6 microns in the CCD. The entire CCD image is read out in frame shift mode at a rate of 15 hertz and individual photo events are identified. The CCD is operated warm with a dark level of 1500-7500e^- and a readout noise of 70e^-.

The principal advantage of an EBCCD is its very high DQE, especially in the far ultraviolet. Estimates of the system DQE for the EBCCD on flight are in excess of 70% at ~95 nm. The primary disadvantages are high voltage (~10 kV) and requirement of a magnet to focus the photoelectrons; traditional magnet assemblies have been bulky and heavy. In addition, magnetic flux from the detector has produced torques on the spacecraft as it changes attitude against the earth's magnetic field. New magnet designs have addressed both of these shortcomings: the overall weight has been reduced by a factor of 3 with virtually no external magnetic flux.

Detective quantum efficiencies of existing detector systems for near ultraviolet wavelengths of 180-300 nm are poor (~10%). Opaque NUV photocathodes on smooth substrates can provide high QEs that are factors of 3 to 4 higher in the NUV than commonly used semi-transparent photocathodes. To work at NUV wavelengths, an EBCCD requires a sealed tube configuration, since current NUV photocathodes are destroyed instantaneously if exposed to air. Sealed tube EBCCDs are expected to be straightforward to demonstrate; such a design should demonstrate peak DQEs ~40% in the NUV within two years. EBCCDs can take advantage of existing Cs_2Te photocathode technology, as well as new photocathodes under development such as diamond or cesiated GaN. Diamond is expected to be very inert in air and therefore could be used in existing open structure EBCCD designs. Development priorities are given in Table 10.

TABLE 10: *EBCCD development priorities.*

EBCCD		
	Development priority	**Possible solution**
	NUV capability	Sealed tube
	Reduction in weight, larger formats	New magnet design

5.2 MCP – Si Array Hybrids

ANOTHER ATTRACTIVE APPROACH in UV detector design is to couple MCPs (with their advantages in format, photon-counting capability, solar-blindness and low background rates) to silicon array readouts. In this concept, the electron cloud output of the MCP intensifier stage is converted to visible light by a phosphor; the visible light is then coupled to the silicon array by a lens or a fiber optic taper. Fiber optic coupling is more common and offers advantages of higher throughput to the array and mechanical compactness.

The resulting light splash on the silicon array can then be read out either in a standard analog-integrating mode (an approach suitable for very high input count rates and used in the SOHO CDS instrument), or in photon-counting mode. In photon-counting mode, individual events detected by the MCP stage and delivered to the readout array are recognized and centroided to a small fraction of a pixel by off-chip electronics. This process can result in very high spatial resolution (limited only by the MCP pore spacing) while operating at a modest MCP gain (desirable for dynamic range and long term stability). The high spatial resolution capability of these systems is particularly well suited for use with the finer pore MCPs that are becoming available.

A number of intensified CCD systems of this type have flown. A recent photon-counting example is the detector for the XMM Optical/UV Monitor Telescope, which will also be flown as part of the Optical Monitor on the Swift Gamma Ray Explorer.

The principal limitation of intensified CCD systems is their severely limited local dynamic range. Accurate photon counting can be performed only if there are not overlapping event splashes within the frame time of the device. For full framing of a large format CCD, the resulting local count rate limits are very low. This problem can be ameliorated somewhat by processing events only in pre-selected windows of interest, a mode available on the XMM-OM, or by using a charge injection device (CID) for the readout array. The addressable architecture of the CID makes it possible to frame different portions of the field at different rates, based on the brightness distribution of the scene.

A new variation based on using an event-driven CMOS Active Pixel Sensor for the readout offers the possibility of completely eliminating the local dynamic range problem. APS technology permits the incorporation of discriminator circuitry within each pixel. When coupled with suitable CMOS logic outside the array area, the discriminator circuitry can be used to trigger the readout of small sub-array windows only when and where an event splash has been detected. Events can thus be detected, readout, and cleared so quickly that the local rate limit will be determined by the intensifier stage itself rather than by the readout array. Readouts of this type will offer a powerful combination of high local and global count rate capability with the high spatial resolution, modest MCP gain requirements and geometric stability common to this class of detector.

6 Long Wavelength Blocking Filters

Finding E
We seek innovative ideas on designing long wavelength blocking filters for efficient use in the ultraviolet with high-sensitivity panchromatic detectors such as CCDs, CMOS-APS and superconducting devices.

In conjunction with development of ultraviolet CCDs and all other high sensitivity panchromatic detectors, including CMOS-APS and superconducting detectors, new ideas and techniques are needed in the design and fabrication of long wavelength blocking filters. Most astronomical objects emit 10^4 to 10^8 visible photons for each far UV photon, and typical ultraviolet filters do not provide sufficient suppression of these visible photons due to out-of-band leakage. In the absence of good, solar-blind blocking capabilities, panchromatic detectors are of limited use in the ultraviolet.

Typical bandpass filters are basically Fabry-Perot interferometers that incorporate metal/dielectric thin films. Current state-of-the-art near ultraviolet filters designed for HST WFC3 have peak transmissions in the near ultraviolet of around 30 to 40% with out of band blocking of 10^{-5} - 2 x 10^{-6}, see Figure 5. In these filters, most of the visible and near-IR light is blocked by a metal dielectric coating, and additional blocking near the band 270 to 400 nm is accomplished using layers of MgF_2 + Al_2O_3.

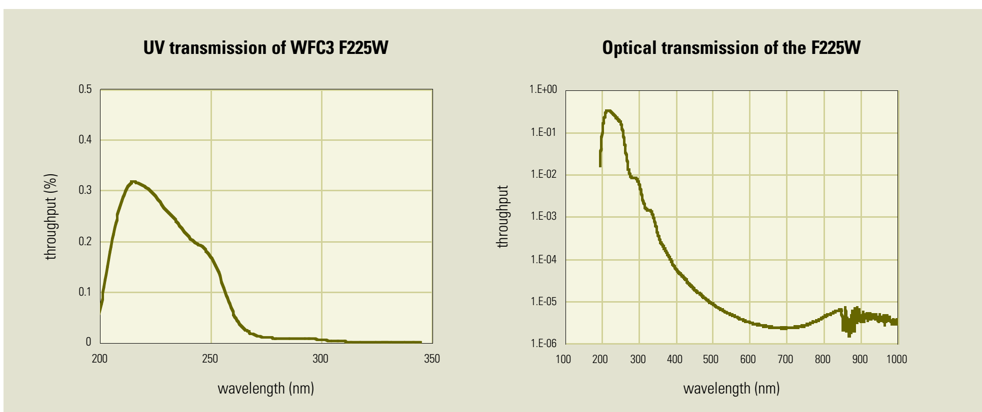


Figure 5: The transmission performance of a flight WFC3 near-ultraviolet filter showing peak ultraviolet transmission (left) and long wavelength cut-off (right).

Wood's filters, which make use of thin alkali metal layers to transmit the ultraviolet and block the visible (to better than 10^{-8}), have been used for HST ultraviolet imaging, albeit with limited success, because their poor ultraviolet throughput (~10%) has been combined with low CCD sensitivity. Wood's filters have a peak transmission at ~150 nm and provide some transmission out to 200 nm. Substantial throughput improvements in the future, perhaps to peak transmissions of ~ 50%, may be realized by careful design and manufacture, although many extensive attempts have been unsuccessful over the past two decades.

Other designs for ultraviolet filters have been proposed, including polymer based ultraviolet absorption filters and tunable filters using a field grating and suitable masking at a relayed pupil. We think that this important area is ready for further research.

7 Development Priorities and Milestones

NO SINGLE CURRENT OR EMERGING detector technology covers, in any optimal way, the UV-Vis spectral region. A multifaceted approach is required. For this reason we find that several technologies should be pursued. Improving the performance of present-day UV-Vis detectors and exploiting new technologies are key components in maintaining a space program of first-rank. Table 11 summarizes the development priorities, solutions and milestones presented earlier.

Over the next three to five years there are a number of areas to address. In the visible, large CCD mosaics are needed for both FAME and KEPLER, which require ~10^8 pixels, and SNAP, which requires 10^9 pixels. Concerns include a loss of manufacturing capability in the U.S. as well as camera design issues and readout and data handling techniques for very large arrays. Methods should be sought to reduce the vulnerability of CCDs to radiation damage as well as to improve ultraviolet response and reduce read noise.

CMOS Active Pixel Sensors will likely replace CCDs when their level of performance, including dark current, read noise and DQE, is improved enough to match present-day CCDs. When this happens, then CMOS technology would be a good approach for constructing very large focal plane arrays: their versatility makes them ideal detectors for space environments. A CMOS APS needs to be developed to TRL 7 with a 1k or 2k square format, and the feasibility of stitching arrays together to form a very large focal plane needs to be demonstrated to TRL 4.

In the ultraviolet, MCP detectors have long been plagued by production difficulties associated with the manufacture of science grade glass plates as well as by low yields of space qualified flight units. There is very limited manufacturing capability in the U.S. For these reasons development of the silicon lithographic technique to TRL 6 is strongly encouraged. This new technology offers many other potential advantages, which include the fabrication of larger devices and improvements to the ultraviolet sensitivity through use of new photocathode materials such as AlGaN. Demonstrations of the silicon plates and new photocathode materials to TRL 6 should be encouraged.

Electron-Bombarded CCDs provide good FUV QE. The EBCCD has very high dynamic range and is comparable in weight, volume and power to MCP detectors. A sealed tube design for NUV applications should be developed to TRL 6.

In the long term, energy resolving detectors such as TESs and STJs will provide unique advantages. They are already envisioned for use at x-ray wavelengths. Space applications of these UV-Vis detectors will need increased fields of view and effective handling of their cryogenic requirements. Within the next five to seven years, a 32 x 32 pixel array should be demonstrated to TRL 7, leading the way to a demonstration flight.

In the absence of good visible light blocking filters, panchromatic detectors such as CCDs and energy resolving detectors are of limited use in the ultraviolet. Despite numerous unsuccessful efforts, we encourage the exploration of innovative ideas to create long wavelength blocking filters to TRL 5 for efficient use in the ultraviolet.

GaN and AlGaN detectors promise huge sensitivity improvements in the ultraviolet. Accordingly, we encourage a vigorous device development effort to create UV image sensors out of these materials, leveraging off the enormous worldwide investment being made in GaN materials research. The primary challenge to overcome before GaN detectors are useful for UV astronomy applications is to reduce the very large non-thermal background produced by material defects. Developing a low noise 256k square device to TRL 7 in the next five to seven years is a very worthwhile goal.

In closing, we make two general comments. First, detector development is by far the most cost-effective way of improving the performance and efficiency of space missions. There is a need to bridge the gap between laboratory proof-of-concept and flight readiness; programs need to be funded to carry the work from TRLs 2 & 3 to the point where they can be proposed for flight, TRLs 6 & 7. Intermediate goals such as rocket and balloon flights can play useful roles in this validation. Programs chosen for satellite missions can rarely afford the cost or time required for significant detector development. Bridging this gap will mitigate risk, contain cost and schedule growth of such missions, and enable deployment of more advanced detectors than would otherwise be used.

Second, the long-term nature of the work required to build astronomical detectors needs to be recognized and sustained. A stable funding profile should be maintained to help protect the knowledge base and to keep expertise together.

TABLE 11.
Development priorities and milestone summaries for many of the detector technologies discussed in the Roadmap.

CCD	**Development priorities**	**Possible solutions**			
	Radiation hardness & CTE	p-type CCDs; charge injection techniques			
	Larger formats	Mosaicing, multiple device packing			
	Reduce read noise	New circuit designs			
	Improve UV QE	Backside treatments			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	Mosaic ~10^8 pixels to TRL8				
	Mosaic ~10^9 pixels to TRL6				
CMOS	**Development priorities**	**Possible solutions**			
	Reduce dark current	Passivation implants, new pixel designs			
	Reduce read noise	New circuit designs			
	Larger formats	Stiching designs			
	Improve linearity	Signal chain circuit design			
	Improve UV-Vis QE	Backside treatments			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	1k square device with good performance to TRL 7				
	Mosaic ~10^8 pixels to TRL4				
AlGaN	**Development priorities**	**Possible solutions**			
	Lower backgrounds	Material quality			
	Larger formats	Device structures			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	256 x 256 array with good performance to TRL 7				
STJ/TES	**Development priorities**	**Possible solutions**			
	Larger formats	Multiplexing, programmable image plane			
	Blocking filters	Solar blind filters, grid filters			
	Increase efficiency	Absorptive coatings			
	Cryogenics	Technology developments			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	32 x 32 array with good performance to TRL 7				
MCP	**Development priorities**	**Possible solutions**			
	Increase UV QE	New photocathodes, and Si-MCP			
	Develop Si-MCPs to full potential	Improve gain			
	Improve resolution	New readout designs			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	1k x 1k Si-MCP device to TRL 6				
	Improve FUV & NUV photocathodes to TRL 6				
	Combine large area Si-MCP with novel anode to TRL 6				
EBCCD	**Development priorities**	**Possible solutions**			
	NUV capability	Demonstrate a sealed tube			
	Reduction in weight, larger formats	New magnet design			
	Development milestones	**Present**	**2005**	**2007**	**2009**
	NUV design to TRL 6				

8 Appendices

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8.2 Acronym List

ACE	Advanced Composition Explorer
ACS	Advanced Camera for Surveys
ALEXIS	Array of Low-Energy X-ray Imaging Sensors
AlGaN	Aluminum Gallium Nitride
APS	Active Pixel Sensors
CCD	Charge-Coupled Device
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CID	Charge Injection Device
CMB	Cosmic Microwave Background
CMOS	Complementary Metal Oxide Semiconductor
CODACON	Coded Anode Converter
COS	Cosmic Origins Spectrograph
CTE	Charge Transfer Efficiency
DQE	Detector Quantum Efficiency
DS1	Deep Space One
EBCCD	Electron Bombarded CCD
ESA	European Space Agency
EUV	Extreme UltraViolet
EUVE	Extreme UltraViolet Explorer
FAME	Full Sky Astrometric Mapping Explorer
FAUST	Far Ultraviolet Space Telescope
FIRST	Far Infrared and Submillimetre Telescope
FUSE	Far Ultraviolet Spectroscopic Explorer
FUV	Far Ultraviolet (115 to 170 nm)
GAIA	(named after Gaea, the greek goddess of earth)
GALEX	Galaxy Evolution Explorer
GaN	Gallium Nitride
HDF	Hubble Deep Field
HRC	(Chandra) High Resolution Camera
HST	Hubble Space Telescope
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAPS	Interstellar Medium Absorption Profile Spectrometer
ICID	Intensified Charge Injection Device
IR	Infrared
IUE	International Ultraviolet Explorer
LED	Light Emitting Diode
MAMA	Multi-Anode Microchannel Array
MICAS	Miniature Integrated Camera & Spectrometer
MCP	Microchannel Plate
MIDEX	Medium-class Explorer
MOSFET	Metal-Oxide-Semiconductor Field-Effect-Transistor
MTF	Modulation Transfer Function
NUV	Near UltraViolet (170 to 300 nm)
ORFEUS	Orbiting & Retrievable Far and Extreme Ultraviolet Spectrometer
OT	Orthogonal Transfer
OTCCD	Orthogonal Transfer Charge-Coupled Device
PC	Photo Conductive
PV	Photo Voltaic
ROSAT	the Röntgen Satellite
QE	Quantum Efficiency
SEC	Sun-Earth Connection
SEU	Structure & Evolution of the Universe

Si	Silicon
SiC	Silicon Carbide
SIM	Space Interferometry Mission
SITe	Scientific Imaging Technologies, Inc
SMEX	Small Explorer
SNAP	Supernova Acceleration Probe
SOHO	Solar and Heliospheric Observatory
SOI	Silicon on Insulator
SQUID	Superconducting Quantum Interference Device
NIST	National Institute of Standards and Technology
STI	Shallow Trench Isolation
STIS	Space Telescope Imaging Spectrograph
STJ	Superconducting Tunneling Junction
STScI	Space Telescope Science Institute
SUVO	Space Ultraviolet-Visible Observatory
TES	Transition Edge Sensor
TIMED	Thermosphere Ionosphere Mesophere Energetics & Dynamics
TPF	Terrestrial Planet Finder
TRL	Technology Readiness Level
UV	UltraViolet
Vis	Visible
VLSI	Very Large Scale Integration
WFC3	Wide Field Camera 3
WFPC	Wide Field Planetary Camera
WFPC2	Wide Field Planetary Camera 2
XMM	X-ray Multi Mirror
XMM-OM	X-ray Multi Mirror-Optical Monitor

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National Aeronautics
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Office of Space Science
Code SZ
NASA Headquarters
Washington, DC 20546

http://spacescience.nasa.gov

Space Telescope Science Institute
3700 San Martin Drive
Baltimore, Maryland 21218

www.stsci.edu/detectors